Nuclear-Rocket Applications

The nuclear rocket will be the key to rapid, practical flight in deep-space missions—lunar ferrying, interplanetary round trips, solar-system probing, rescues, and satellite maneuvers

BY PAUL G. JOHNSON

NASA OFFICE OF PLANS
AND PROGRAM EVALUATION
WASHINGTON, D.C.

THREE years ago, in an issue of *Astronautics* devoted to advanced propulsion systems,[1] the great potential of nuclear-rocket propulsion was emphasized.[2,3] The desirability of specific-impulse values of several thousand seconds was made clear, and the long-range objectives of nuclear-rocket research and development were pointed out. That is, if we want to thoroughly explore the solar system without requiring men or machines to spend lifetimes enroute, we must equip ourselves with extremely high-performance propulsion systems and vehicles.

The emphasis in this issue is on the near-term nuclear-rocket situation. The importance of achieving high plateaus of performance has not diminished.[4] Several years of wrestling with the practical problems of design, fabrication, and testing have not altered the long-range picture. However, the prospect of soon having an operational propulsion system calls for basic planning for its use. Consequently, a considerable effort has been directed toward near-term applications of nuclear rockets.[5,6]

Both points of view are important. Exploitation of early capability is a natural step in the over-all program which need not slow our progress toward advanced systems. The total development plan should form a continuum from first generation to what we now view as ultimate performance.

Here we will look at nuclear-rocket applications in the near and intermediate future, and consider only solid-core reactors.

Our space goals call for initial exploratory gathering of information and, ultimately, the regular transport of men and materials to remote points of interest. Such space activities entail the development of launch vehicles, space transportation systems, space probes, and other special-purpose vehicles. The following table lists the categories for potential application of nuclear rockets.

TRANSPORTATION SYSTEMS
Upper stages on chemical-rocket launch vehicles
Recoverable launch vehicles
Lunar ferries, 24-hr-orbit ferries
Interplanetary round-trip vehicles

SPECIAL-PURPOSE VEHICLES
Solar-system probes, planetary orbiters
Maneuvering satellites, rescue vehicles

This is not to say that nuclear rockets will be used in all of the categories; competing propulsion systems may pre-empt many areas.

Three propulsion-system types, widely discussed, are being developed for such future applications: high-energy chemical rockets, nuclear (thermal) rockets, and nuclear-electric systems. The table outline on page 24 gives a brief summary of their characteristics.

Chemical and nuclear rockets employ high-thrust engines with moderate specific-impulse capability. Nuclear-electric systems employ low-thrust engines with high-specific-impulse capability. The basic dissimilarity between high- and low-acceleration spaceflight makes a comparison of performance very difficult. The time element cannot be readily related to payload or hardware cost. Comparison among high-thrust systems is much more straightforward, although cost analyses are always subject to spirited debate.

The time for definite association of particular propulsion systems with particular applications has not yet arrived. For neither type of nuclear system do we know an availability date or the limiting powerplant characteristics. Performance estimates remain on a parametric basis, although the uncertainties are gradually narrowing down. However, as will be shown in the following discussion, these estimates offer sufficient hope of improved capabilities to justify development of prototypes and research in areas which may lead to major improvements. The safest prediction is that there will be uses for all types in the future of spaceflight, once they are developed.

Launch Vehicles. The use most frequently proposed for Nerva is to propel an upper stage of a Saturn-class launch vehicle.[7] The expected thrust level of the Nerva powerplant is appropriate to the stage weight, and operational demands on the powerplant are moderate. A generalized estimate of payload performance for nuclear rockets in third-stage applications appears in the graph here below. The ratio of payload to third-stage initial (gross) weight is plotted versus the impulsive velocity increment, ΔV_{imp}, beyond a low-altitude satellite orbit (e.g., 100 n. mi.). The third-stage is assumed to start from a suborbital condition such that a ΔV of 5000 fps must be applied to reach the parking orbit. Thus, the total ΔV of the stage is 5000 fps plus the value shown on the abscissa.

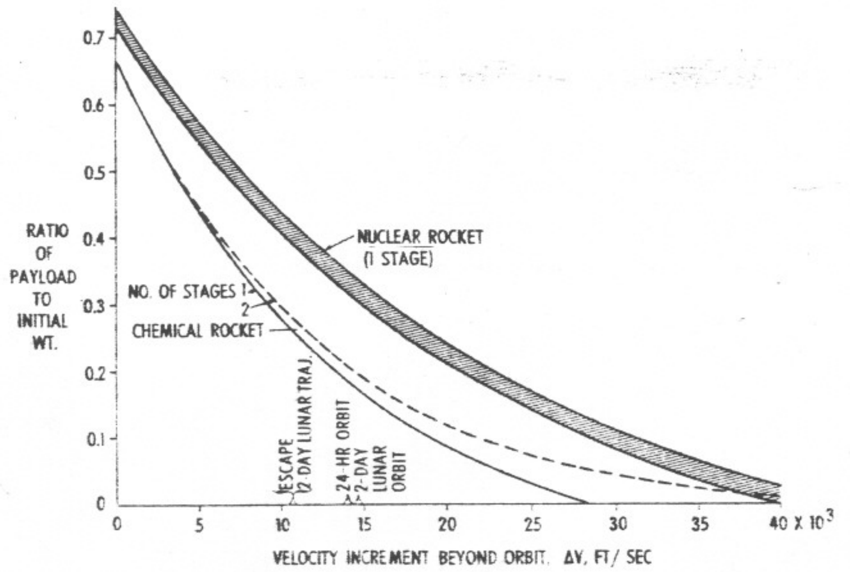
The graph at bottom compares the estimated payload fractions for nuclear- and chemical-rocket third stages. The crosshatched band shows the performance of a single nuclear-rocket stage starting from the prescribed suborbital condition. The lower pair of curves show the corresponding payload fractions for one- and two-stage chemical-rocket vehicles. Indicated on the abscissa are the ΔV requirements for several likely uses for these vehicles, assuming the propulsion systems to be capable of the necessary re-starts.

To make this data even more specific, the table shown here lists payloads for the several missions and the two propulsion-system types, based on an initial weight of 300,000 lb at third-stage start. This data comes from a simplified analysis and is not intended to correspond exactly to a particular launch vehicle, such as a Saturn C-5. Nuclear-chemical payload ratios are also presented in the table. Such ratios should be applicable to a wide range of vehicle sizes.

PAYLOAD PERFORMANCE OF 300,000-LB THIRD STAGES

Suborbital start—ΔV_{imp} to 100 n.mi. orbit, 5000 fps: specific impulse, 425 sec for chemical system and 800 sec for nuclear.

Mission	Payload, lb			Ratio of nuclear payload to chemical (1-stage) payload
	Chemical rocket		Nuclear rocket (1-stage)	
	1-stage	2-stage		
100-n.mi. orbit	200,000	200,000	214,000	1.07
Earth escape	76,000	84,000	118,000	1.55
Lunar trajectory (2-day trip)	76,000	84,000	118,000	1.55
24-hr-orbit	56,000	62,000	96,000	1.72
Lunar orbit (2-day trip)	52,000	59,000	92,000	1.77



Comparison of nuclear- and chemical-rocket third-stage performance, suborbital start. ΔV_{imp} to 100-n. mi. orbit, 5000 fps; specific impulse, 425 sec (chemical) and 800 sec (nuclear).

The comparisons presented in both the graph and table here show that the use of nuclear-rocket third stages on chemical launch vehicles results in a significant (but unspectacular) improvement in performance. A payload increase of 50 to 80% for Saturn-class vehicles will be very welcome. However, there will be an interim during which chemical-rocket development leads that of nuclear rockets. Chemical launch vehicles of much larger lift-off weight may have superior payload capabilities at the time when early nuclear stages become available. Therefore, this payload advantage, which is based on early nuclear-rocket thrust levels, would not by itself justify a nuclear-rocket development program.

To realize further advantage from nuclear rockets in launch-vehicle propulsion, reactor powers must increase. For example, a nuclear rocket of 20,000 Mw is required to match the million-pound thrust of the chemical-rocket second stage of the Saturn C-5. (A handy rule for nuclear rockets: Thrust (lb) $\cong$ Power (Mw) × 50.) A development trend in this direction is logical for the intermediate term, giving payload capabilities for earth-orbit and lunar missions of over twice those of all-chemical vehicles.

In the more distant future, however, our hope for a great expansion of space activity seems to rest on the development of recoverable and re-usable launch vehicles. The goal will be single-stage-to-orbit boosters which can return to the launch site and, with a minimum of maintenance, be used for many more flights.

Despite the desirability of high specific impulse for this application, the development of recoverable nuclear rockets is not a sure thing. The operational problems associated with the recovery and launching of "hot" reactors will be severe. The prospects therefore look better for early realization of recoverable chemical boosters than for nuclear.

Flight experience with nuclear rockets will help clarify the outlook in this area. On the other hand, high specific impulse may result in improvements in recovery techniques by permitting more liberal use of propulsion during controlled descent. This would be an important argument for attempting recoverable nuclear rockets. At present, however, the use of nuclear rockets in launch vehicles does not appear to be as strong a long-term justification for their development as some of the higher-energy missions, such as manned interplanetary flight.

Ferry Vehicles. When the weight and cost of the propulsion system are significant parts of the weight and cost of the entire space vehicle, re-use may give economy. Each case must be evaluated individually to find the break-even point. Interorbital ferries are often cited as desirable transportation-system types. A lunar ferry, traveling from earth orbit to lunar orbit and back, has been proposed.[7] A ferry between low and high orbits is also a possibility if traffic volume warrants. The latter might be called a 24-hr-orbit ferry.

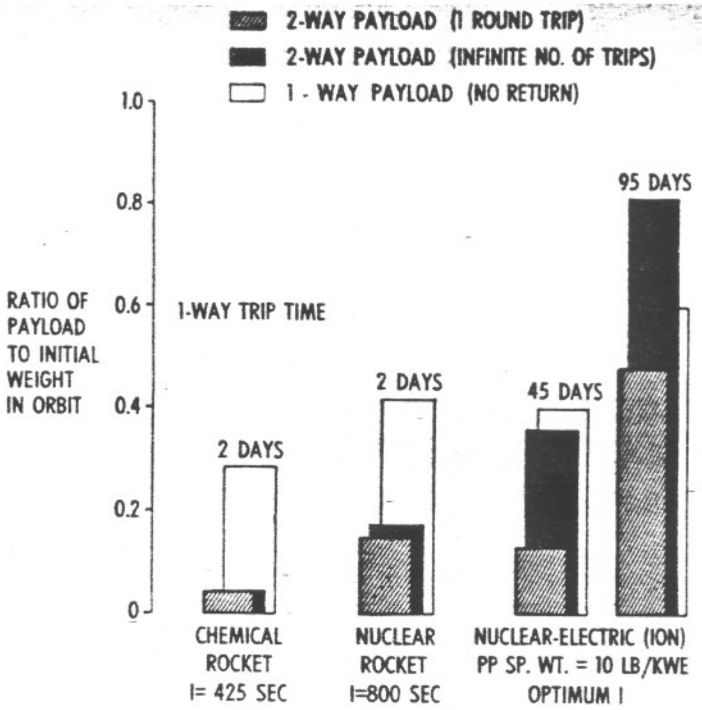
The chart at top here gives a comparison of lunar-ferry payloads. Lunar ferries and 24-hr-orbit ferries are characterized by very similar total velocity increments, so only one is illustrated. Bar height indicates the ratio of payload to weight in low-earth orbit. Also given are data for chemical rockets, nuclear rockets, and nuclear-electric (ion) systems.

THE performance of each propulsion system is represented by three superimposed bars. The crosshatched area corresponds to the single-trip payload of a ferry which carries equal payloads to and from the lunar orbit, as might be the case for passenger transportation. The black bar shows the ratio of total payload to total weight in orbit (payload plus propellant, in the limit) for an infinite number of round trips. The third bar, shown unshaded, presents the performance of a one-way vehicle which does not return to low orbit.

The chart illustrates several factors which enter the evaluation of the ferry technique. This evaluation must ultimately rest on economics, with due consideration given to performance, costs, operational aspects, and traffic volume.

From a performance standpoint alone the low-specific-impulse systems—chemical and nuclear rockets—gain little from re-use; the big advantage to re-use of a nuclear-rocket ferry would

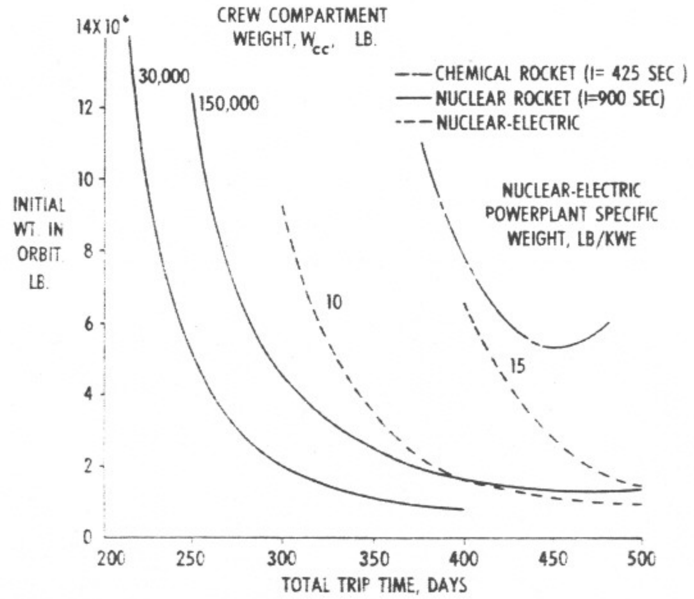
PAYLOAD COMPARISON FOR LUNAR FERRIES



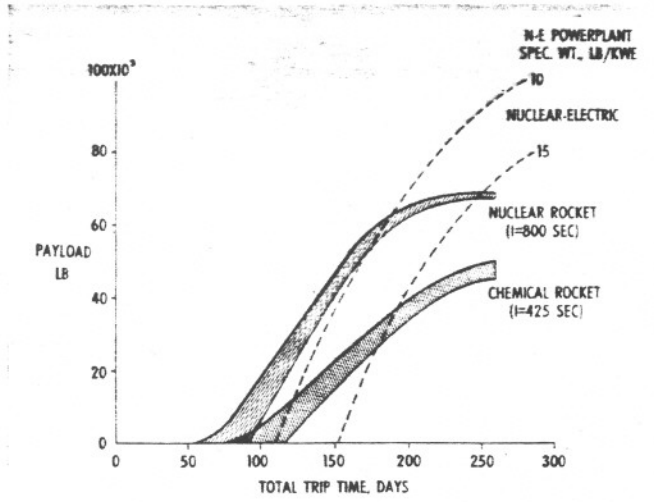
CHARACTERISTICS OF SPACE PROPULSION SYSTEMS

Type	Typical values*		
	Thrust / Vehicle wt.	Specific impulse, sec	Powerplant wt., lb / Jet power, kw
Chemical (H_2-O_2)	⩾ 1.0	425	(Negligible)
Nuclear (solid core)	0.2–1.0	750–900	0.001–0.01
Nuclear-electric (ion)	0.5×10^{-4} – 5×10^{-4}	3000–10,000	10–50

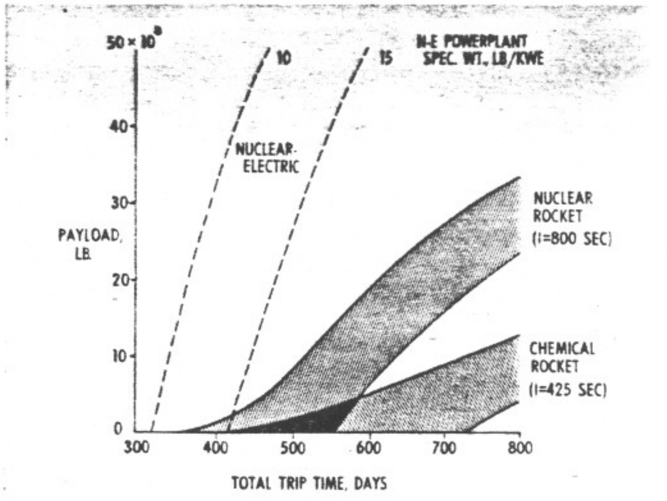
* These values and ranges of values are illustrative only. A consideration of parameter selection processes is beyond the scope of this article.



Effect of trip time on initial weight of manned Mars vehicle, seven-man crew; exploration equipment weight, 60,000 lb; re-entry-vehicle weight, 30,000 lb; and crew-compartment weight, 150,000 lb (unless otherwise noted).



Trip-time effect on payload of unmanned Mars orbiters; initial weight in orbit, 200,000 lb.



Trip-time effect on payload of unmanned Saturn flyby probes; initial weight in orbit, 200,000 lb.

be in saving reactor cost. On the other hand, the nuclear-electric system would gain considerably from re-use because the powerplant is such a large part of the vehicle weight and the propellant weight is relatively small.

UNFORTUNATELY, trip times are long for low-acceleration systems. Two trips are shown,[8] corresponding to two thrust-weight ratios, and a powerplant specific weight of only 10 lb/kwe is assumed. By selecting a low-thrust and high-specific-impulse operating condition (relative to other nuclear-electric systems, that is) nearly one-half of the vehicle weight can be put into lunar orbit and an equal amount returned. However, each trip takes three months each way. Powerplant lifetime would have to be greatly in excess of a year to permit re-use on such a schedule. If a higher-thrust operating condition were used, the trip time could be cut in half, but the payload fraction would drop to that of a nuclear-rocket vehicle. Furthermore, a trip time of 1.5 months is still long for impatient passengers.

The implications that can be drawn from the chart on page 24, which presents only the performance picture, are that high-acceleration vehicles will be favored for human transportation, because of trip-time considerations, and that low-acceleration ferries will be favored for freight transportation, because of the payload ratios attainable. Whether nuclear-rocket or nuclear-electric ferries are actually put into service will depend on the over-all economics of the situation and on the re-usability of the propulsion systems.

In this connection, the demands of such a mission on the propulsion systems are severe. A nuclear rocket would have to restart many times and accumulate many hours of operation. Shutdown, aftercooling, and re-start would have to be routine procedures. On the other hand, a nuclear-electric powerplant must be capable of operating at design power for well over a year. Moreover, if the powerplant specific weight should be as high as 20 lb/kwe, the trip times would be double those in the chart. Then, too, a low-acceleration system would spend relatively long times in the Van Allen belts, making serious demands on the radiation-sensitivity limits of the payload or on the required shielding.

Nuclear-electric systems may be uniquely competitive with high-thrust ferries whenever the payload needs a high electrical-generating capacity. Rather than employ a ferry to transport both the payload and the power source to a 24-hr orbit, for example, the power supply could bootstrap itself up to the high orbit by means of electric rockets (arcjets, in this case). Once again the practicality depends on the importance of transit time. The user must analyze his total operation to evaluate the complication caused by many weeks of orbit-raising time. The user must also answer the question of how much payload power is required, since propulsion power is generally much larger than most payloads would consume.

Further study of the nuclear-rocket ferry is expected to promote this application to a position of importance. The ferry vehicle could be part of lunar-base or orbiting-station logistics when transport of men and materials becomes fairly regular. Despite the attractiveness of the concept, however, the success of lunar or orbiting stations does not hinge on the availability of a nuclear-rocket ferry. Hence, we must look to even more demanding applications for a justification of nuclear-rocket development.

Manned Interplanetary Vehicles. The space task most frequently cited as a justification for nuclear-propulsion-system development is manned interplanetary transportation,[7] for two clear reasons:

1. Mars stands out as the most fascinating object for space exploration in our lifetime.
2. The difficulties involved in a manned Martian round trip appear so great that a high-performance propulsion system seems essential.

TWO facts support the second reason: Energy requirements of just moderately fast round trips (about 400 days) are such that nuclear rockets possess an initial-weight advantage over chemical rockets approaching an order of magnitude;[6] and a great desire exists to cut trip times down to only a few months.

Achievement of extremely rapid transit to Mars will require a major breakthrough in propulsion technology. The gaseous-core nuclear rocket is a prime contender; but the solid-core nuclear rocket can take us a significant way in the desired direction. Chemical rockets are obviously further out of the picture when times are shortened. And if nuclear-electric systems are to make the journey in much less than a year, the powerplant specific weight must be reduced well below 10 lb/kwe.[9]

The graph on page 24 shows the effect of trip time on initial weight in earth orbit for manned Mars round trips. A simplified mission has been selected for illustration, involving a crew of seven men, a stay time of only about a week in Mars orbit, a Mars exploration payload of 60,000 lb, and an earth re-entry vehicle weight of 30,000 lb. The crew-compartment weight, consisting mostly of solar-flare shielding, is nominally 150,000 lb,[10] but the effect of reducing it to 30,000 lb is indicated for the nuclear rocket.

The variations of initial weight with trip time shown in this graph for chemical, nuclear, and nuclear-electric systems illustrate three points. First and most apparent, chemical rockets are far behind in the race, and the nuclear-electric powerplant specific weight must be below 10 lb/kwe to compete with the nuclear rocket; an electrical power of over 40 Mw will be necessary to keep the nuclear-electric trip time below 400 days. The second point is that a large reduction in shield weight results in a substantial improvement in trip time, as indicated by the two solid curves. Thus, the gathering of better data on solar-flare hazards will be followed with great interest by the planners of interplanetary flights. Finally, the over-all conclusion is that nuclear-propulsion systems reach points of rapidly diminishing returns for round-trip times in the neighborhood of 8 to 12 months.

THE importance of trip time in manned spaceflight will demand considerable attention as interplanetary missions are planned. Faster journeys require heavier vehicles or more-efficient propulsion systems, but there may be compensating improvements in reliability, safety, and over-all program effectiveness—that is, having enough time between the return or arrival at destination of one vehicle and the launch date of the next to integrate new information effectively into later missions. Since the time between optimum launch dates to Mars is about two years, trip time could be a critical parameter in a Mars-exploration program.

Interplanetary transportation of nonbiological cargo will also be involved in space exploration, and nuclear propulsion will be highly desirable in this area also. Round trips may be required for delivery of supplies and return of scientific data or materials. One-way trips may be more common, since re-use of the vehicle or salvage of equipment is likely to be uneconomical. Either type of nuclear propulsion system can be considered for cargo transportation. Final choice will depend on the availability and characteristics of operational powerplants.

The operational demands on an interplanetary nuclear-rocket propulsion system may not be severe. Because of the large differences in desired thrust from one propulsion period to the next, and considering the propellant loss that prolonged aftercooling would entail, the most economical procedure may be to discard the orbital-launch rocket after use. Thus, the largest reactor would not have to start again after the orbital-launch maneuver. The most stringent requirement would then be the startup of the Mars braking rocket after several months of coasting through space. Since this powerplant would probably also be used for leaving Mars orbit, one restart would be involved. Furthermore, the assumption that atmospheric braking upon return to earth will eliminate the need for any rocket braking means that the Mars-departure reactor can be discarded without further aftercooling or re-start.

The required variety in thrust level would mean that several sizes of nuclear-rocket powerplant must be developed. A 2-million-lb orbital-launch stage would require a reactor power of about 10,000 Mw; a Mars-departure stage would require only about 1000 Mw.

Probes and Orbiters. The possibility of using nuclear rockets to propel solar-system flyby probes and orbiters has been proposed,[6,11] although this area is usually thought of as the province of nuclear-electric propulsion.[9,12,13] Nuclear rockets are considered for two reasons: Trip times to the near planets can be reduced by the use of high-thrust rockets, and the possibility exists that nuclear rockets will have the required capability before nuclear-electric systems. This speculation is beyond our scope here, but the trip-time comparison can be made.

The application of nuclear rockets to unmanned scientific spacecraft requires the development of powerplants which have low weight at low power. This characteristic can be attained through selection of appropriate reactor types and materials. The need for a "lightweight" reactor is stated as a definite requirement on the basis of the assumption that many scientific payloads would be small, weighing less than a "heavy" nuclear-rocket powerplant. In this situation a few thousand pounds of powerplant weight would have a large effect on the number of interesting missions which could be accomplished.

LET us look at two planetary objectives to see the capabilities and limitations of nuclear rockets in the probe and orbiter area—a Mars orbiter and a Saturn flyby probe. The Mars trip illustrates the difference in attainable trip time between high- and low-acceleration spacecraft. The Saturn flyby illustrates the potential advantage of nuclear-electric systems for trips to the outer solar system.

The graph on page 25 shows the variation of payload with trip time for Mars orbiters propelled by nuclear rockets, chemical rockets, and nuclear-electric propulsion. The bands for the high-thrust systems indicate the difference between two- and one-stage orbital-launch vehicles (upper and lower boundaries, respectively). If we take for granted that chemical rockets, coming first in time, will handle the small-payload preliminary probe missions, we may restrict our attention in this graph to larger payloads, for example, upwards of 20,000 lb. In this region the nuclear rocket will reduce the trip time by 30% from that required with an all-chemical rocket. A one-stage nuclear rocket will also outperform a two-stage chemical vehicle. Another way to take advantage of nuclear-rocket performance would be to use a smaller launch vehicle.

It can also be seen from the graph that a nuclear-electric powerplant must weigh less than 10 lb/kwe to compete with a nuclear rocket for trips of under six months. With no premium on time, an electric spacecraft could carry higher payload fractions, but the operational aspects of a planetary program are likely to be greatly improved by trip shortening. The situation would be analogous to the manned program except it eliminates crew-safety considerations.

Our final graph on page 25, shows quite a different picture. Saturn is such a distant destination that ballistic trajectories require either very long times or very large propellant weights. Even with a 200,000-lb initial weight and a payload requirement of only 5000 lb, a chemical rocket would take about 20 months. A nuclear rocket could do as well with a single stage. A two-stage nuclear rocket would require a trip time of 15 months. Although these times are undesirably long, the graph shows that the mission can be accomplished by these means if they are the only ones available.

The nuclear-electric systems, taking advantage of the great distances and weak gravitation field, show very impressive performance for outer-solar-system missions such as the Saturn flyby. Nuclear-electric powers of four to eight electrical megawatts are implied in the illustrated performance data. Higher powers go with shorter trip times. On early flights small payloads could be carried on spacecraft weighing much less than 200,000 lb. For example, boosters of the early Saturn class (20,000 to 30,000 lb in orbit) could be used if operating times of 400 to 450 days are acceptable and if a powerplant weighing only 10 lb/kwe can be developed at the lower power (under a megawatt). Furthermore, no additional payload power supply would be required if the primary source was still operating.

The potential use for two-stage nuclear rockets in this vehicle-weight range points up the need for a lightweight reactor. That is, powers of only 1000 and 240 Mw would be required for first and second stages in the examples cited in the last two graphs. An additional 5000 lb of powerplant would erase much of the nuclear rocket's advantage over the chemical rocket in low-payload applications.

Concluding Remarks. While the development of nuclear rockets is now being carried on without firm commitment to specific applications, the need for high performance is becoming clearer. Each step we take in space exploration strengthens our conviction that we will go on to the planets and expand our activities in many forms of space transportation. To accomplish our more ambitious goals we must, because of economic considerations, look to nuclear propulsion.

The strongest case for nuclear rockets is based on manned Mars expeditions. The high-energy requirements make chemical rockets too expensive, and the desire for short trip time puts electric propulsion at a disadvantage. Even advanced solid-core nuclear rockets fail to satisfy our desire for rapid transit. Nevertheless, until a breakthrough in technology makes even higher performance available, the nuclear rocket is the key to rapid spaceflight.

Nuclear rockets will find other applications in the over-all space program. Early use of nuclear rockets in launch-vehicle second or third stages will significantly augment the payload capacity of chemical boosters. Lunar or inter-orbit ferries for human transportation will probably use high-thrust nuclear propulsion, and scientific probes and orbiters could also benefit from development of an appropriate nuclear-rocket powerplant.

The principal goal for the near future of nuclear rockets is to attain operational status. A combination of high performance and reliable operation must be demonstrated. Success in this task will open the door to significant advances in spaceflight and will lead, ultimately, to the development of routine space transportation.

References

1. *Astronautics*, Vol. 4, No. 12, Oct. 1959.
2. Bussard, R. W., "Boundary Conditions for Nuclear Propulsion," *Astronautics*, Vol. 4, No. 10, Oct. 1959.
3. Rom, F. E., "Advanced Reactor Concepts for Nuclear Propulsion," *Astronautics*, Vol. 4, No. 10, Oct. 1959.
4. Hunter, M. W., Jr., "The Potential for Nuclear Propulsion for Manned Space Flights," paper presented at IAS National Meeting on Manned Space Flight, St. Louis, Mo., May 2, 1962.
5. Jordan, W. Y., Jr., Saxton, D. R., and Thomas, P. G., "Nuclear Rocket Stages Increase Saturn's Payload Capability," *Aerospace Engineering*, Vol. 20, No. 5, May 1961.
6. Rom, F. E., Lietzke, A. F., and Johnson, P. G., "Small Nuclear Rockets for Space Propulsion," *Nucleonics*, Vol. 20, No. 11, Nov. 1962.
7. Dryden, H. L., Statement to Subcommittee on Research, Development and Radiation of Joint Committee on Atomic Energy, U.S. Congress, Sept. 13, 1962.
8. Edelbaum, T. N., and Gobetz, F. W., "Mission Capabilities of Ion Engines," Contract NAS5-935, Phase II-Final Report, UAC RL Report R-1297-9, March 1962.
9. Hayes, R. J., Hoffman, M. A., and Stuhlinger, E., "The Manned Electric Rocket Challenge," ARS Report 2222-61, Oct. 9-15, 1961.
10. Himmel, S. C., Dugan, J. F., Jr., Luidens, R. W., and Weber, R. J., "A Study of Manned Nuclear-Rocket Missions to Mars," *Aerospace Engineering*, Vol. 20, No. 7, July 1961.
11. Cooper, R. S., "Applications for Low-Power Nuclear Rockets," *Astronautics*, Vol. 6, No. 8, Aug. 1961.
12. Spenser, D. F., Jaffe, L. D., Lucas, J. W., Merrill, O. S., and Shafer, J. I., "Nuclear Electric Spacecraft for Unmanned Planetary and Interplanetary Missions," JPL Technical Report No. 32-281, Apr. 25, 1962.
13. Speiser, E. W., "Performance of Nuclear-Electric Propulsion Systems in Space Exploration," JPL Technical Report No. 32-159, Dec. 15, 1961.

◆◆